

# A Technique for the Assessment of Flight Operability Characteristics of Human Rated Spacecraft

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**In support of new human rated spacecraft development programs, the Mission Operations Directorate at NASA Johnson Space Center has implemented a formal method for the assessment of spacecraft operability. This “Spacecraft Flight Operability Assessment Scale” defines six key themes of flight operability, with guiding principles and goals stated for each factor. A standardized rating technique provides feedback that is useful to the operations, design and program management communities. Applicability of this concept across the program structure and life cycle is addressed. Examples of operationally desirable and undesirable spacecraft design characteristics are provided, as is a sample of the assessment scale product.**

## I. Introduction

THE design of a human rated spacecraft is a complex and costly process requiring the integrated assessment of many individual criteria. Historically, it has been difficult to include in that integrated assessment the design’s full impact on the flight operations community. The unique “operability” requirements have not been well understood, nor has there been a well-defined set of criteria for assessing operability. As programs approach their operational phases, program managers and flight operations organizations alike are often surprised when faced with difficult and costly operations implementations. A formal means of forecasting operability issues during the development phases of a program is therefore necessary to reduce operations phase costs.

The challenge in addressing flight operability needs for a new program is threefold: (1) there is no accepted, universal definition of flight operability, (2) there is no clear mapping of flight operability needs to program and vehicle requirements, and (3) there is no formal method to assess flight operability characteristics given a spacecraft design and mission definition. Development of a practical flight operability assessment methodology requires the establishment of several key items. Flight operability itself must be defined in terms that are relevant both to the flight operations community and to program management. Specific operability goals must be set, preferably as formal design and performance requirements. Objective measures must be established to determine compliance with those requirements.

Several organizations have attempted to define flight operability and specific associated design requirements. The European Space Agency (ESA), NASA Jet Propulsion Laboratory (JPL), and NASA Lyndon B. Johnson Space Center (JSC) have all published documents intended to better specify operability needs. ESA’s Space Segment Operability Standard addresses robotic spacecraft operations safety, efficiency, and cost effectiveness but recognized the difficulty in defining clear criteria for onboard automation capabilities.<sup>2</sup> NASA JPL defined a similar set of design criteria for its robotic spacecraft. To document similar lessons learned for human spaceflight, NASA JSC published its own Space Systems Operational Design Criteria Manual.<sup>3</sup> Each document provides a valuable resource of design suggestions, but none fully encompasses the needs for human rated spacecraft nor provides a clear process for the evaluation of real system designs against documented recommendations.

The challenges associated with establishment of this methodology are not unlike those faced by the aircraft flight test community in the 1950’s and 1960’s. Over the course of twelve years, a technique for the characterization of an aircraft’s handling techniques – as assessed by the pilot operating the aircraft – was developed by George Cooper

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<sup>1</sup> Deputy Chief, Constellation Systems Integration Office, Space Transportation Vehicle Division, Mission Operations Directorate, Mail Stop DS15.

<sup>2</sup> Space Engineering Space Segment Operability, European Cooperation for Space Standardization, ECSS-E-70-11A, 5 August 2005.

<sup>3</sup> Space Systems Operational Design Criteria Manual, NASA JSC Mission Operations Directorate, 1 November 2004.

and Robert Harper.<sup>4</sup> The Cooper-Harper Scale has long stood as the standard tool for aircraft handling assessment. Modified versions of this scale are employed widely in the assessment of crew equipment and interfaces for NASA human rated spacecraft.

In response to these challenges, the Mission Operations Directorate at NASA JSC has established a formal method for the evaluation and communication of a spacecraft system design's operational characteristics. The spacecraft flight operability assessment method described in this paper is born of the desire to identify the operations systems drivers and critical requirements that are a significant influence on operations cost, schedule, performance and risk. This process is not intended to replace or replicate other critical assessments such as risk, reliability or safety assessments. Instead, this new technique adds to a program's assessment toolset a means to address the concerns and potential cost drivers that are unique to the operational phase of a program and the flight operations community.

## **II. Flight Operability Definition**

Apollo 11 flight director and former director of NASA JSC's Mission Operations Directorate Eugene Kranz defined the flight operations infrastructure as a system designed to "Maximize mission success, to minimize risks to the [vehicle] and the crew, to decrease operating costs, and to achieve an effective balance in the application of all operational resources."<sup>5</sup> In this context, the measure of a system's flight operability is the measure of the degree to which that system enables a balance of maximum mission success, minimal risk, and minimum operating cost. Because the flight operations community is held to the highest standards of safety and mission success, the most variable of these factors is typically operating cost.

Any measure of flight operability must encompass the impact on cost, responsiveness and risk incurred in safely executing intended operations with a spacecraft as designed and manufactured. Cost is driven by both the developmental investments required to build the operations infrastructure (facilities, operations techniques and products, and trained personnel prepared to execute operations), by the recurring cost of maintaining that infrastructure and by the expense of executing mission planning, training and operations over the entire operations phase. Responsiveness reflects the duration over which an operation must be planned, reviewed and executed. Excessive time requirements reduce the availability and responsiveness of operations. Risk is the likelihood of success or failure of the operation. Additional consideration of risk must be given in the case that a failure endangers crew health, vehicle integrity or mission success. "Operations Integration" is the practice of weighing and balancing these factors.

Flight operability is not only a function of the vehicle design, but also the mission requirements that the system must support. Therefore, a given system design may have different operability "scores" for different types of mission scenarios and operations. Consider a vehicle designed solely to achieve and maintain Low Earth Orbit may exhibit significant propellant margin in performing that mission. That same vehicle design may provide little or no margin if the mission is changed to achieve and maintain a lunar orbit. Therefore, a complete measurement of flight operability begins with the definition of the system or vehicle under study, the specific mission class, or mission phase, or more detailed operational scenario in which operability is to be assessed. For that specific set of design and mission conditions, an operability assessment must identify and objectively assess the key influences that impact flight operations ability to meet safety, mission success and operating cost constraints.

## **III. Programmatic Impacts of Flight Operability**

Although flight operability issues may be most apparent to those who execute mission planning, training, and real-time support activities, the impact of these issues can span across an entire program infrastructure. Spacecraft with low operability characteristics force the program, vendor, and operations communities to pursue complex tradeoffs between cost categories. Conversely, spacecraft with high operability characteristics do not require significant program-level operations cost tradeoffs. Consider an operability issue associated with a hazardous condition or operation. To reduce risk of a life threatening hazard, additional time and resources are spent in the analysis, planning, practice and execution of special procedures that mitigate the hazard. These are collectively referred to as "operational workarounds." Failure to perform such analysis, planning, practice and diligence in

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<sup>4</sup> The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, *George E. Cooper and Robert P. Harper, Jr., April 1969.*

<sup>5</sup> Eugene F. Kranz, STS Flight Operations – Concept versus Reality. AIAA Shuttle Environment and Operations Conference II, November 1985.

execution results in greater risks should that the hazard be experienced. The implications and costs associated with this hazard and associated operational workarounds are categorized below.

#### **A. Engineering and real-time operations support cost impact**

Program sustaining engineering costs are incurred whenever operational workarounds are invoked. For example, the International Space Station was initially certified to fly in only a very narrow range of attitudes. However, operational needs mandated that the spacecraft be maneuvered to and through a much wider range of attitudes in response to testing needs, off-nominal conditions, and the constraints of other docked spacecraft. Thermal analysis of each alternate attitude for ISS operations became a continuous task for the program throughout the program's operations phase. The result was the need for additional personnel and tools to perform the analyses needed to support each mission and operation.

#### **B. Program responsiveness impact**

Program and mission responsiveness are also reduced when operability is not provided. The constant need for new analysis, new operations product development, and verification of these new products can cause weeks- or even months-long delays, in addition to increased operating cost, when making even changes to mission execution.

The late discovery of multiple concerns regarding the ISS solar arrays resulted in the addition of many conflicting operational constraints on the orientation of the arrays. The daily task of planning solar array positions quickly changed from that of a basic capability of the flight control team to an effort requiring the constant involvement of a much larger team including vendor and program office engineering analysts, the development of new tools and processes, and a still evolving set of data products. The additional processes required to handle these challenges necessarily impact the timeliness within which changes can be made.

#### **C. Mission success impact**

Program reliability is reduced when adequate operability is not provided. Dependence on operators to "close the loop" for basic spacecraft functional capabilities leaves open the potential for human error and, in the case of requirements levied on ground-based operators, ties spacecraft reliability to ground network and communication satellite asset reliability. Any break in the chain of facilities and services that enable the operator to implement an operations workaround negatively impacts the overall reliability of the integrated vehicle-ground support system.

During early International Space Station (ISS) operations, Mission Control Center operators were required to send hundreds of commands per day just to maintain ISS communication capability. These commands provide Tracking Data Relay Satellite System (TDRSS) pointing and selection data to onboard processors that are not able to adequately perform automatic selection. This left the vehicle prone to potential communications outages as a result of human error or onboard failures - that could impact science return. Again, an operational workaround could be provided, but the cost and risk associated with the workarounds had an impact on flight operations and the program at large.

### **IV. Addressing Flight Operability Issues at the Program Level**

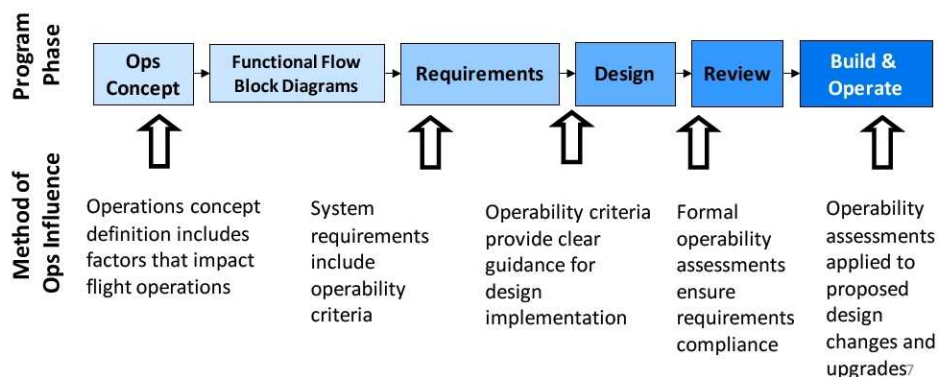
The Cooper-Harper Scale grew from a basic assessment tool to means of asserting formal operations-related performance requirements for aircraft designers. Over the span of a dozen years, the scale was refined and applied over a wider set of cases. Today, aircraft and spacecraft requirements documents typically specify minimum acceptable Cooper-Harper scores. This was the result of the general acknowledgment that the assessment technique added value, generated repeatable results, and that those results could be clearly and predictably mapped to design characteristics.

Similarly, the definition of a formal technique for spacecraft flight operability should be viewed as an evolutionary process, beginning with a common definition of operability definitions and assessment criteria, but eventually reaching a common understanding that positively influences design requirements. A mature, program-endorsed operability assessment technique therefore can be integrated into several phases of a given program life cycle. The assessment methodology described in this paper is intended to provide a first step in the achievement of these goals.

Operability expectations can be explicitly addressed in the development of program operations concepts, addressing the needs associated with mission planning, training, and execution activities. The requirements development process can be better informed through these operations concept details, and specific performance operations-driven requirements may be derived from the definition of operability criteria. Design activities and design reviews can benefit from operability guidelines as well as operability assessments that identify key issues



early in the design process. Finally, the same methods may be used to assess operability of changes and upgrades to be made during the operational phase of a program.



**Figure 1. Flight Operability considerations throughout the program life cycle**

Formal flight operability assessment practices may be applied to both development and operational programs. For development programs, the Spacecraft Flight Operability Assessment Scale can and should be employed in generating inputs at formal design reviews (Subsystem Design Review, Preliminary Design Review, Critical Design Review) in less formal design team forums, and in the assessment of formal Change Requests (CRs). For operational programs, the scale may be applied to proposed incremental vehicle changes such as hardware upgrades and flight software updates. This includes the assessment of CRs, Problem Reports, and other notices that request or direct operational workarounds.

Operability assessment techniques should not replace other critical evaluation methods such as operations concern or “watch lists,” Review Item Discrepancy (RID) submittals, hazard assessments or risk assessments. Similarly, operability assessments should not replace or replicate other critical assessment techniques that address safety, performance, and life cycle cost. Instead, operability assessment adds to those other methods by defining and assessing the factors that are unique to the flight operations community.

## V. Primary Themes in Flight Operability

Review of the many individual recommendations of the flight operations community indicates six major operability themes – simplicity, margin, robustness, flexibility, situation awareness and control. These themes are discussed below. Note that, if not properly balanced, these operability themes can pose conflict. Features that make a system more robust may also make the system more complex. The judgment of subject matter experts must be applied to strike balance in these cases.

### A. Simplicity

Simplicity – often referred to with its inverse, complexity – is the collective measure not only of the functions, interfaces and dependencies inherent in the system architecture, but also of the observations, decision and actions required of the human operator. The number and ease of operation of functions and interfaces in the operational environment drive the number and cost of analyses, tools, procedures, plans, constraints and training required. Simple systems that have few dependencies and few possible system configurations generally require fewer procedures, less training, and less effort to monitor and control.

To address operability concerns, hardware and software should be as simple as practical, minimizing the number of unique interfaces, algorithms, and functions that require separate operational techniques to monitor and control. Functions and interfaces should be common and consistent, requiring a reasonable number of tasks and methodologies on the part of the operator. Tasks themselves should be simple, allowing the operator to concentrate on decisions to be made rather than detailed operational sequences to be performed.

There are reasonable limits on the operationally desirable level of simplicity. A system that is so simple that it does not provide the flexibility or robustness to perform in off-nominal scenarios is not operationally viable. Careful consideration of the other operability factors should be included in an assessment of the appropriate level of simplicity in a system.



## **B. Margin**

Operational margin describes the amount of capability or consumable supplies available beyond that required to execute the mission. Operational margin provides assurance that the nominal mission may be safely executed and allows for continued operation in the event of unexpected conditions such as malfunction or mission scenario changes.

There are three categories of operational margin:

- Performance Margin - The ability of the system to provide greater capability than required for normal operation or in the event of any single failure. Measures of performance margin vary by vehicle subsystem. For example, performance margin for an electrical power system might be measured by power output capability while the measure for a communication system might be associated with the data bandwidth sizing.
- Resource Margin - The amount of consumable commodities (propellant, atmospheric gases, stored energy) available beyond that required to support nominal flight operations.
- Environmental Tolerance Margin - The system's ability to operate beyond the nominal operations environment for a given mission profile.

Often, operational constraints and controls are required to ensure that adequate capability is available throughout a nominal mission and after an anomaly. These constraints and controls typically impact the ability to successfully complete all mission goals, as they limit the use of capabilities and resources even before an anomaly occurs. They also require the addition of more techniques, tools, products and training to the operations infrastructure. All of these additions result in increased life cycle cost. Margin is considered available for operational consideration only when formal analysis documentation of that margin is made available to the operations community.

Lack of margin can have profound impacts on mission planning as well as real-time operations. More detailed pre-flight analysis must be performed to ensure that mission objectives may be met within the available resources, that the vehicle can perform required operations within its normal performance envelope, withstand potential anomalies, and that the flight environment does not exceed the vehicle's limits. Lack of margin not only impacts the mission operations organization, but it also drives significant program sustaining engineering costs to provide additional case-specific analyses that support the flight operations community as well as program strategic planning.

Flight systems should therefore provide margin in order to minimize operations constraints. Vehicle thermal, power, and communications capabilities should not be designed with operations constraints that result in the necessity for highly optimized mission timelines to accomplish normal operations such as rendezvous, proximity operations, and docking. Margin in all three of these categories is a significant driver in determining the amount and extent of mission- and activity-specific planning and analysis. Significant positive margins in key categories should be available in all mission phases.

At the same time, excessive margin is not operationally desirable. For example, a system that provides resource quantities beyond any credible need may use so large a fraction of the allowable mass that fewer redundant strings are provided in the design. Expectations on available margin should be bounded by the maximum needs for an operational scenario (including off-nominal scenarios). In addition, care should be taken in scenarios that involve failure "stacking" (inclusion of multiple separate failure cases in one scenario). Credible failure scenarios include those that would allow continued mission execution and those that would initiate the abort or early termination of a mission. Failures after those that drive a mission abort or early termination are generally out of scope.

## **C. Flexibility**

Flexibility is the ability of the system to accommodate change. This change can be to the mission scenario or to the vehicle configuration. When a system is inflexible, even small changes to the mission or vehicle configuration may require operational workarounds – additional tasks and responsibilities placed on operations personnel and facilities. Flexibility is generally defined by the system's architecture.

Flexible flight systems should be easily reconfigured or updated to account for new conditions and new capabilities during flight or between flights. Although this applies to both flight hardware and flight software, the impacts of inflexible software are the more acute. Operational experience often identifies necessary changes to limits, gains, and other parameters used by flight software. If recompilation of flight software is required to update such parameters, then these value updates will be costly and will require months or years to incorporate. Operational workarounds will be required for extended periods in order to account for discrepancies between the desired and provided values.

There are reasonable limits to the desired degree of flexibility for an operable system. While some amount of flexibility is desired to allow for slight variation in mission profile and vehicle configuration, excessive flexibility

can result in additional operations challenges. Highly flexible systems may require more training, product development, and manual tending than is operationally desirable or affordable.

#### **D. Robustness**

Robustness describes the system's ability to cope with changing conditions resulting from both nominal and off-nominal operations. Flight operations planning and analysis costs are often driven by the need to "protect" the system or vehicle from certain conditions and events. The nature and degree of these "protection" measures is determined by the system's or vehicle's robustness. Note that provisions such as performance margin and consumables margin is assessed in a separate "margin" category. The "robustness" category addresses redundancy, fault tolerance, cross-strapping and similar system architecture traits.

To achieve operational robustness, flight systems should be designed to maintain fail operational capability (no loss of functionality after first failure); the design should ensure no single failure puts the mission in to a contingency. Systems should remain partially capable in off-nominal scenarios, allowing the continued use of remaining functionality without requiring significant operator action to recover that functionality. In many cases, cross-strapping - interconnections between components of two or more separate strings - are effective means for improving robustness in off-nominal scenarios. Redundant strings should be supported by separate data and power utility feeds to allow continued system availability after a single failure.

No time-critical operator action should be required to prevent loss of mission, crew or vehicle. Time-critical operator actions are those that must be performed by a person within a limited time frame immediately following an event to ensure continued safe and effective mission execution. In general, the vehicle should automatically identify and reconfigure in response to failures that can impact mission success or crew/vehicle survival. Automated responses should result in predictable vehicle configurations that support crew and vehicle survival.

The need for robustness is somewhat bound by the overall goals and mission scenarios that define the system and its operation. For a given spacecraft, a set of reference missions and configurations defines cases in which the vehicle is expected to either complete or abort the mission. Robustness should be provided to support mission execution within the expected bounds (including off-nominal scenarios) and to support mission abort or early termination once the defined criteria have been met. Robustness beyond that needed for these cases may not be warranted.

#### **E. Situation Awareness**

Situation Awareness (SA) is the ability to perceive the state of the vehicle and its operational environment, to understand that state, and to project the future state based on that understanding. If systems do not inherently support SA, additional operator tools and techniques may be required to provide this insight and understanding. This may drive additional operations cost and infrastructure such as facility changes, procedures, training, or even additional flight control team staffing. The inability to identify specific anomalies in some scenarios may increase risks to mission, crew and vehicle. As a result, some activities or objectives may be disallowed when SA cannot be maintained.

Situational awareness should be assured through appropriate telemetry and caution and warning messages which allow unambiguous detection and verification of all nominal and off-nominal events. Appropriate sensor locations and quantities, as well as telemetry display/downlink capabilities should allow the operator to verify automatically generated cues. Simple indications to the operator should be provided for failures with widespread vehicle impacts. No false positive or false negative failure indications should be provided to the operator.

A balanced approach should be taken in assessing situation awareness. Maintaining SA requires the operator to have an overall understanding of the system's state, capabilities and environment. Too much data can make this understanding almost as difficult to maintain as can too little data.

#### **F. Control**

Control measures the degree and difficulty with which the operator can direct the system's performance during operation. This includes not only the availability of all of the control capabilities to appropriately configure the system, but also the level of control that the operator must exercise. Use of low level commands – those that control individual items at a fine level – may be necessary at times to accomplish specific needs. However, reliance on only these low level commands can result in high operator workload because each component must be individually configured to accomplish a goal. Higher level commands – those that cause the system to perform multiple steps to achieve a predefined configuration – can greatly reduce the level of difficulty in operating the system. Accordingly, one effective measure of control is the average count of the number of commands required to implement desired courses of action.

Ineffective commanding capabilities may require the development of additional ground-based software tools to support the configuration management, processing, and issuance of commands in an effective manner. Additional procedures may be required to support the configuration and processing of commands. Additional training is required to enable operators to use these tools and procedures. All of these add to the infrastructure, cost and time associated with controlling the spacecraft.

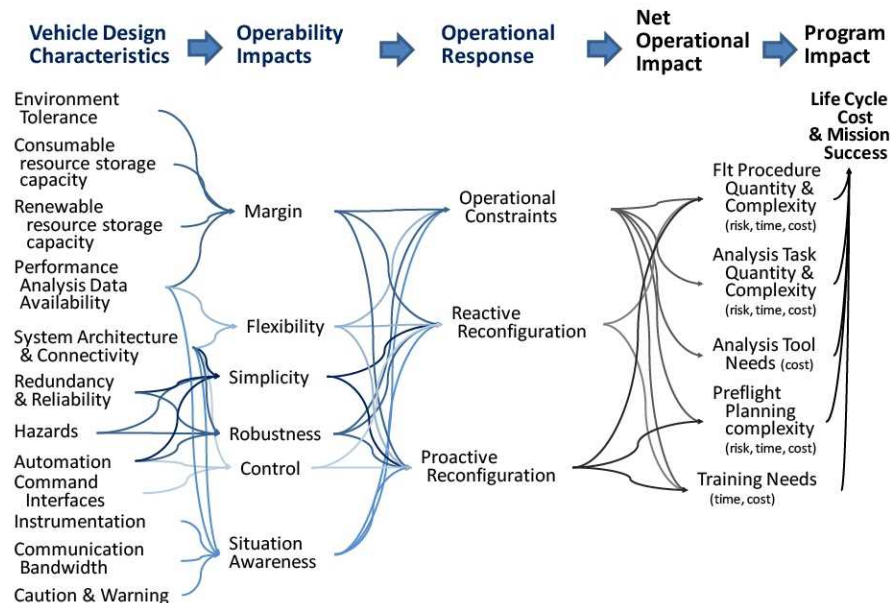
Command capabilities should allow the operator to control vehicle functions by setting goals and providing decisions when queried. Once these goals and decisions have been provided by the crew, the vehicle implements them with little or no additional work required on the part of the crew. Routine functions (those that always involve the same steps executed in the same order) should be automated. Where appropriate, low-level commands should still be provided to allow for effective operations in off-nominal situations.

The system should operate and respond in a repeatable, predictable manner to each command. The operator should have control over the execution of automated capabilities, allowing him/her to proactively prevent or reactively terminate the execution of inappropriate actions. The operator should have the capability to correct the vehicle configuration when automation either fails to do so or places the vehicle in an undesirable configuration.

Automation may be applied to address some control needs, but automation may also create other operability challenges. In general, automation of well understood operations is achievable and operationally desirable. However, automation of actions or responses to scenarios that are not well understood can make operations more difficult. Where automation functions must be monitored by operators, halted as required, and replaced by operator actions, the automation function may be operationally undesirable. Even in well understood scenarios, the flexibility to modify automation through the use of reconfigurable scripts, settings, and other flexibility measures is highly recommended.

## G. Balancing Operability Themes

There exists a complex association of individual design characteristics with these operability factors, as illustrated in Figure 2. The details of these associations require a more thorough discussion than can be provided in this paper alone.



**Figure 2. Vehicle design characteristic influence on flight operability.**

The complex nature of these influences, and the tendency for some of these themes to conflict, make more complex the task of establishing formal analytic techniques for operability assessment. Just as is the case with the Cooper-Harper scale, then, it is most prudent to rely on flight operations personnel to perform operability assessments and assess these complex interrelationships and conflicts.



## VI. Spacecraft Flight Operability Assessment Scale Content and Structure

The flight operability assessment scale borrows elements from both the Cooper-Harper Scale and typical program risk assessment scales, both of which are illustrated in Figure 3. The overall structure of the scale, including its grading range – from one to ten with one being the most desirable score – is reminiscent of the Cooper-Harper Scale’s graphical layout. The more detailed textual criteria included in the scale, however, bear closer similarity to risk assessment tools.

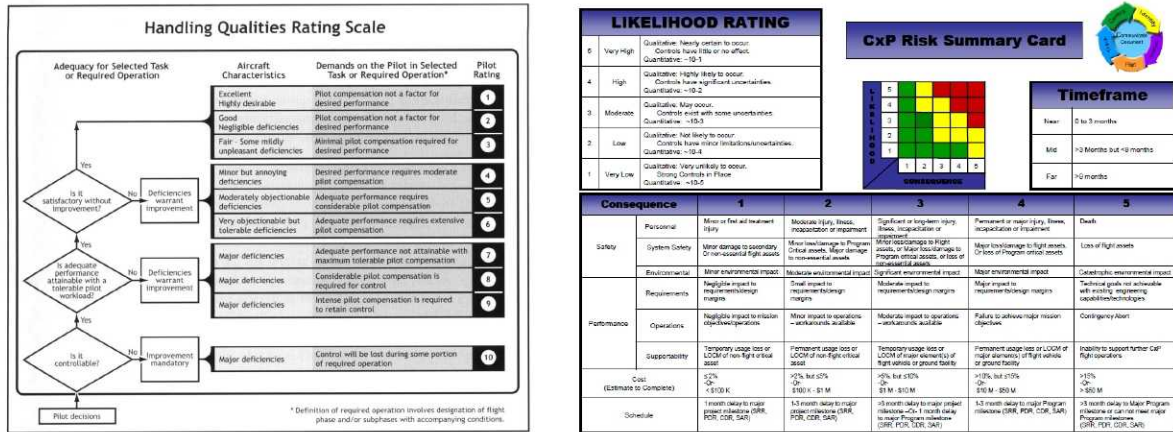


Figure 3. Cooper-Harper (left) and risk assessment (right) scales.

The scale incorporates three basic elements – a set of operability themes to be evaluated, criteria with which to evaluate each characteristic, and a grading scale to normalize the results. The operability themes correspond to the six operability themes discussed above – simplicity, margin, flexibility, robustness, situation awareness and control. Flight operability criteria, as shown in Figure 4, are posed to categorize assessments of each operability theme: “Can the mission be accomplished?” “Can it be accomplished within tolerable limits (workload, cost, risk)?” “Can it be accomplished within normal limits?” and “To what degree?” These four questions guide the assessor in determining which color coded range within the possible 10 scores should be assigned for an operability theme.

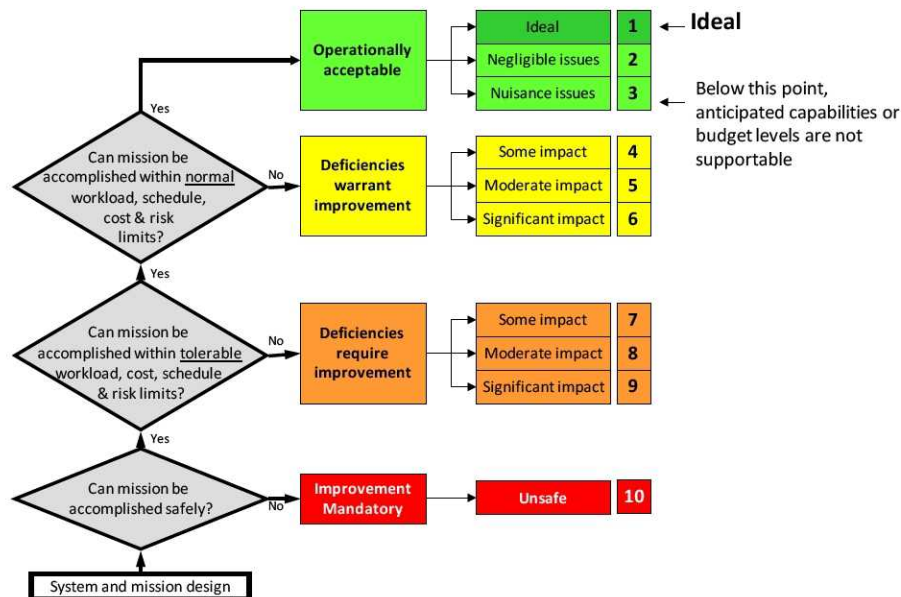


Figure 4. Operability assessment criteria.

The rating scale provides the remaining guidance – in the form of operational and program impact statements - to select the specific rating within a category. Ratings are expressed in terms meaningful to flight operations

personnel and to program management. Each number rating has a specific operational impact statement, as shown in Figure 5. More generalized program impact statements are mapped to ranges of rating values as well. To provide clear guidance regarding application of these ratings to each of the six operability factors, a set of customized flowcharts are provided.

Operational Impact		Programmatic impact
1	Excellent operations capabilities	<u>Operationally desirable.</u>
2	Negligible operational challenges that can be handled with no noticeable impact to operations feasibility or cost	<u>Mission can be accomplished</u> Minimal operational impacts can be handled within existing infrastructure and budget with negligible workload impacts.
3	Operational challenges cause noticeable nuisances to the operator, but can be handled with little impact to operations feasibility or cost.	
4	Operations are difficult and incur significant <u>one time</u> costs (manpower, facilities, products, etc.) to ensure mission success. Some mission objectives may not be achieved.	
5	Operations are difficult and incur significant <u>recurring</u> costs (manpower, facilities, products, etc.) to ensure mission success. Some mission objectives may not be achieved.	<u>Some mission objectives may be at risk.</u> Operational impacts will change infrastructure requirements, cost allocations, work prioritization, etc. from the baseline operations plan.
6	Operations are difficult, mission objectives may remain at risk even after additional investments (manpower, procedures, facilities, etc.) are made.	
7	Operational challenges reduce mission capability and degree of mission success by preventing some objectives	
8	Operational challenges put mission success at risk. No operational techniques are available to mitigate risk.	<u>Mission is at risk.</u> Operational impacts will exceed the capabilities of either the operations community or the entire program.
9	Operational challenges increase risk of loss of crew or vehicle. No operational techniques are available to mitigate risk while preserving mission content.	
10	Operationally unsafe or unachievable	
		<u>Not operable.</u>

Figure 5. Operability grading criteria.

These elements – the operability themes, criteria and grading scale, are integrated into a single graphical depiction as shown in Figure 6. In each case, both a numeric result and a textual description of strengths and deficiencies is given. More detailed guidance for each of the six operability themes is provided in a customized version of this graphic for the theme of interest. These more detailed graphics are included in the appendix to this paper.

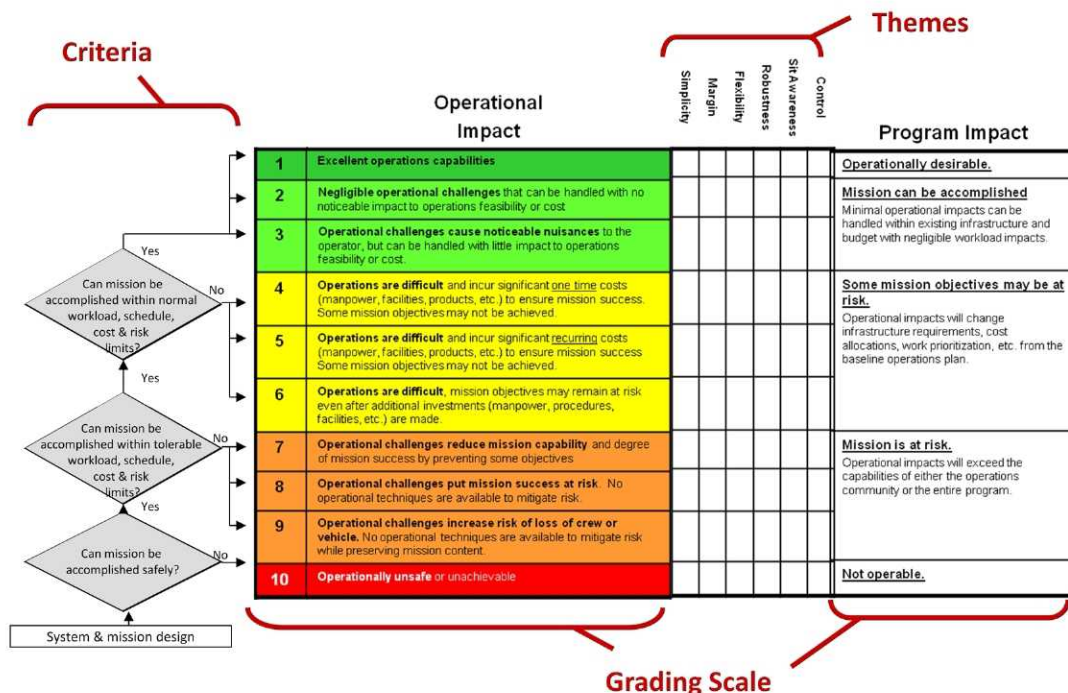


Figure 6. Integrated elements of the Spacecraft Flight Operability Scale.



The scale is best applied to assessment of specific flight systems or spacecraft functions, such as Guidance, Navigation and Control (GNC) or attitude control in specific flight phases, such as ascent or docking. The scale allows the reviewer to summarize the operational impacts of one or multiple design features of those systems in those operational scenarios. Application of this scale to individual subsystem components such as Line Replaceable Units (LRUs) is generally not recommended, as the operability aspects of a system involve more than just the LRU. The software supporting that LRU, the user interface displays providing command and control for the subsystem, and the interrelationships of that unit with other subsystem components all have a direct impact on the flight operability. Capabilities and issues associated with each LRU can, however, be factored into the subsystem-level assessment of flight operability.

It is important to address not only the system design itself, but also the test and verification strategy as part of system development and delivery. While an initial design may indicate that margins exist, that a system has adequate redundancy, or that the system performs to a given specification, none of these characteristics are truly known unless the system is appropriately tested. The test and verification criteria should be inspected as a part of operability assessment to ensure that design goals are met.

## VII. Initial Experiences in Applying the Scale

The Mission Operations Directorate at NASA JSC has begun using this scale as a tool for both operational vehicles such as the Space Shuttle and for new vehicle designs such as those developed under the Constellation Program. To date, assessments of 46 Space Shuttle Orbiter subsystems have been completed for ascent, orbit and entry scenarios. An integrated review of these results is underway to ensure consistency. Assessment of currently operational vehicles serves to calibrate the assessment scale by identifying areas in which clearer guidance must be given to ensure consistent evaluation results regardless of the person performing the evaluation or the system under evaluation.

Operability Theme	Score	Description	Operational Impact	Program Impact
Simplicity	5	Multiple nominal and off nominal procedures as well as operational workarounds to disable and release dampers indicate inherent undesirable complexity in the system.	Complexity increases operator workload, requiring additional tools and techniques (procedures, constraints, etc.).	Some mission objectives may be at risk.
Margin	8	Little margin is available in the APDS hooks. Single hook out cases drive the need for significant system workarounds (PMA hooks, FR constraints etc). Single point jam on the ball screw mechanism could lead to loss of mission.	Inadequate margin induces risk of loss of mission.	Mission is at risk.
Flexibility	3	The semi-automatic docking sequence allows for much greater system flexibility but also poses issues with added training due to it's complexity.	Functions enabling flexibility induce additional operator workload within reasonable limits.	Mission can be accomplished.
Robustness	8	Capture latches require manual reconfiguring after the first failure to return to a nominal configuration. A single point jam on the ball screw mechanism can cause loss of mission.	Inability to recover sufficient functionality increases risk of loss of mission.	Mission is at risk.
Situation Awareness	3	In general, enough insight into the health and operation of the docking system is available to MCC. Some coordination with crew to attain crew only insight (A7 panel lights add to MCC workload.	Required effort to maintain Situational Awareness results in minor workload impacts.	Mission can be accomplished.
Control	3	Lack of ground control capability limits MCC ability to operate the docking system in off nominal situations.	Command & control interfaces and tasks impact workload but remain in reasonable limits.	Mission can be accomplished.

Figure 7. Sample of a completed flight operability assessment for Space Shuttle docking system during orbit operations.



An example of an assessment of a Space Shuttle subsystem in this format is shown in Figure 7. The comments shown in this example illustrate many of the typical operational impacts of spacecraft design. The subsystem scores relatively well in the categories of flexibility, situation awareness and control, though some limitations capabilities are noted. However, the system's scores in simplicity, margin and robustness scores reflect the significant operational impacts of even a single failure in the subsystem.

Initial use of this scale within the operations community has yielded encouraging results. Evaluators find the scale easy to use, and the resulting evaluations quickly identify and isolate operability issues within specific subsystems and scenarios. For user convenience, a pre-formatted spreadsheet form is used to assist the evaluator.

## VIII. Conclusion

There is more work to be done in the development and industry-wide adoption of formal flight operability expectations. There has been good success in initial steps to isolating the major criteria that define flight operability. Early efforts to apply the scale to operational programs demonstrate that the scale can be applied across many different spacecraft systems, and that the evaluation process extracts useful feedback regarding design characteristics and operability impacts. Through the continued application of this process to existing and future programs, it is hoped that the scale and supporting material can be both matured and disseminated to a wider audience within the aerospace community.

## Appendix

Graphical desictions of the Spaceflight Operability Assessment Scale and related detailed rating guidance for individul operability themes are provided below

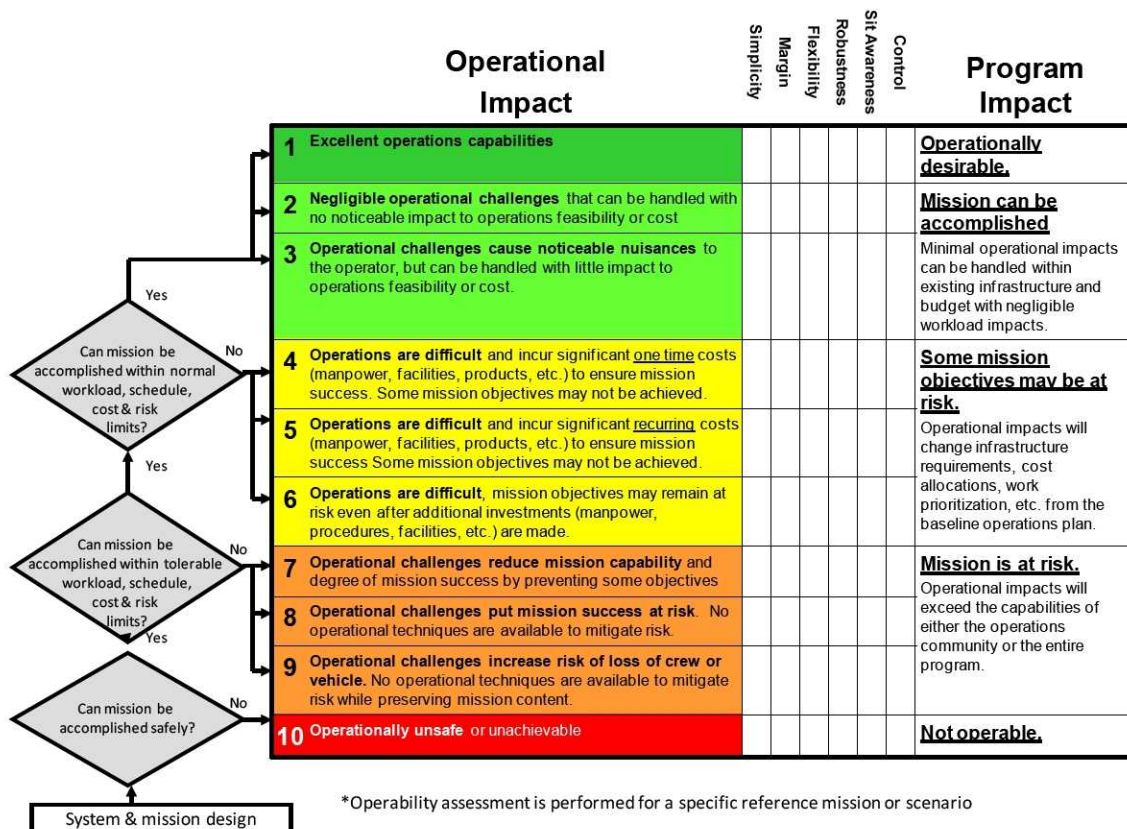


Figure 8. Spacecraft Flight Operability Assessment Scale.

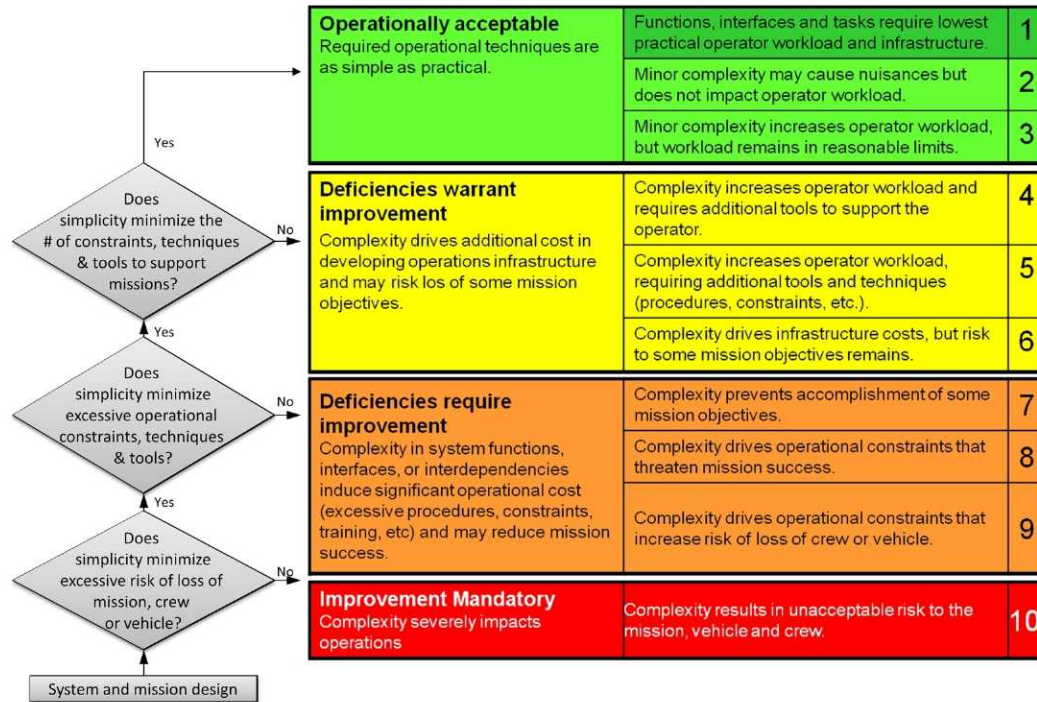


Figure 9. Detailed guidance for assessing simplicity.

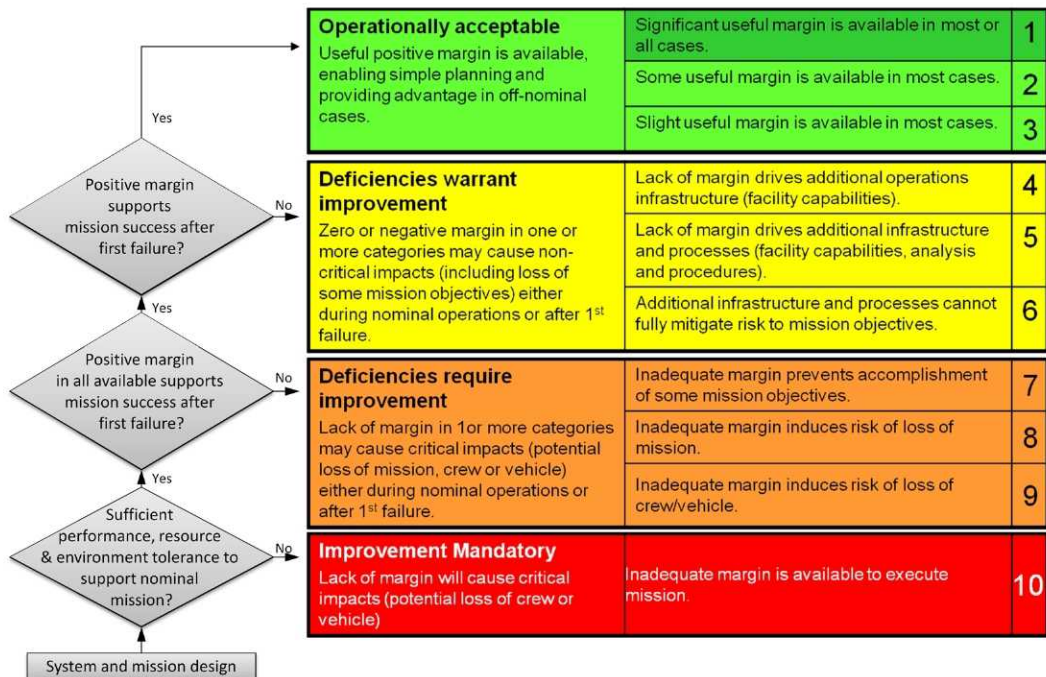


Figure 10. Detailed guidance for assessing margin.



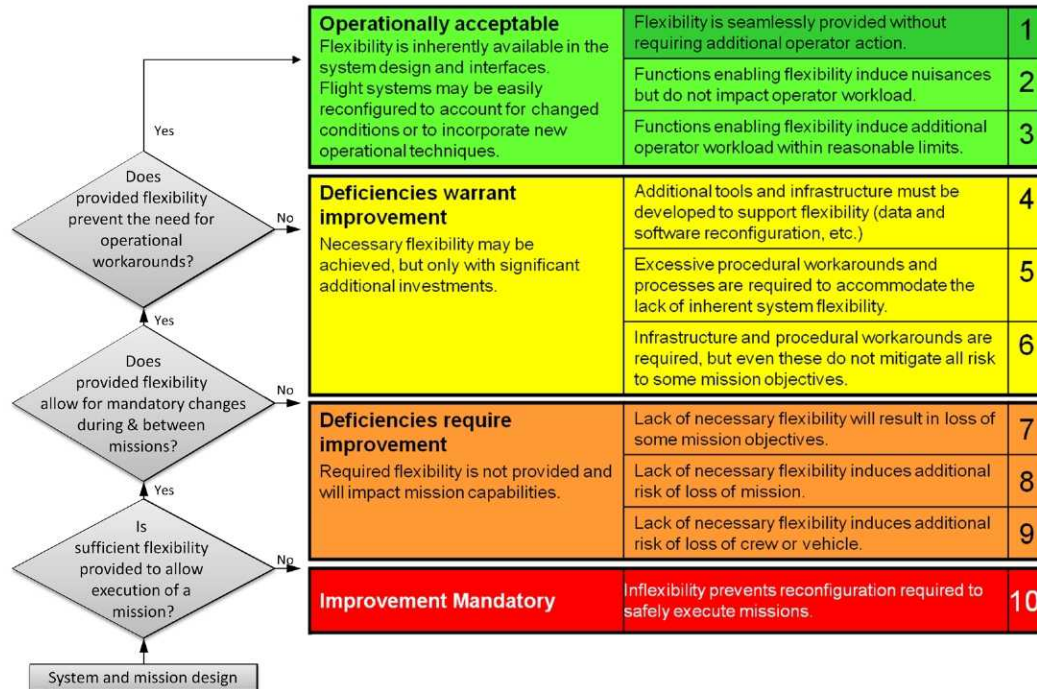


Figure 11. Detailed guidance for assessing flexibility.

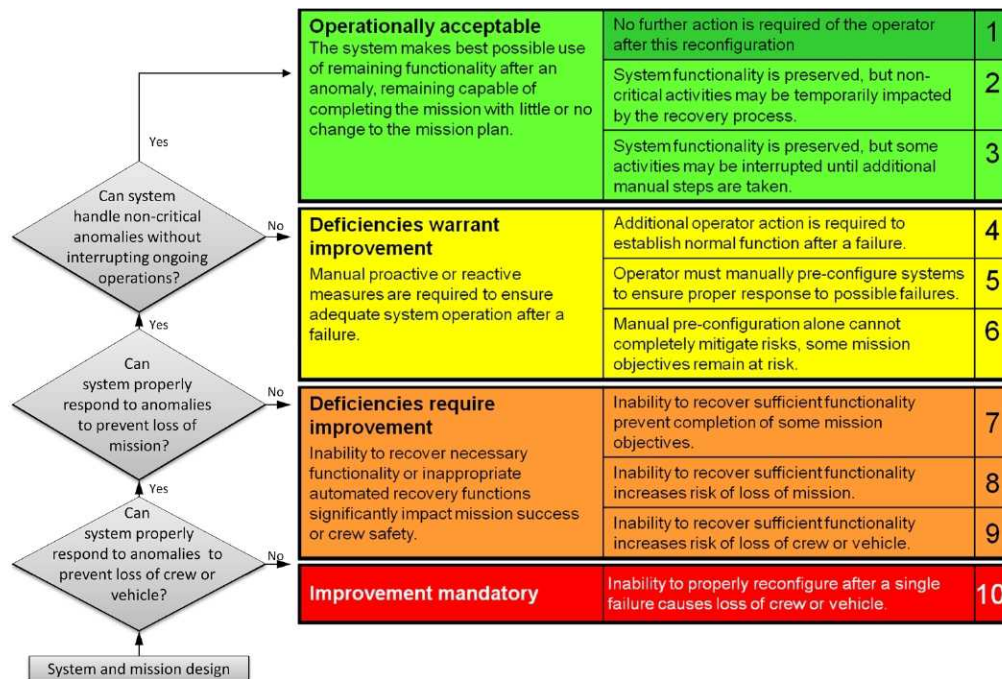


Figure 12. Detailed guidance for assessing robustness.



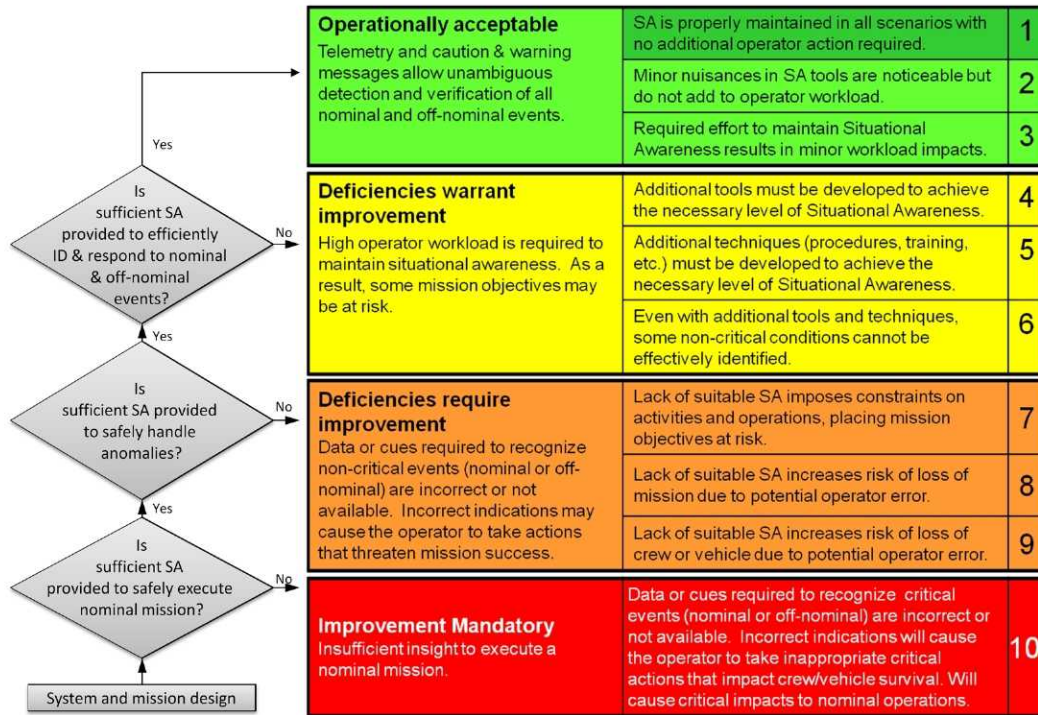


Figure 13. Detailed guidance for assessing situation awareness.

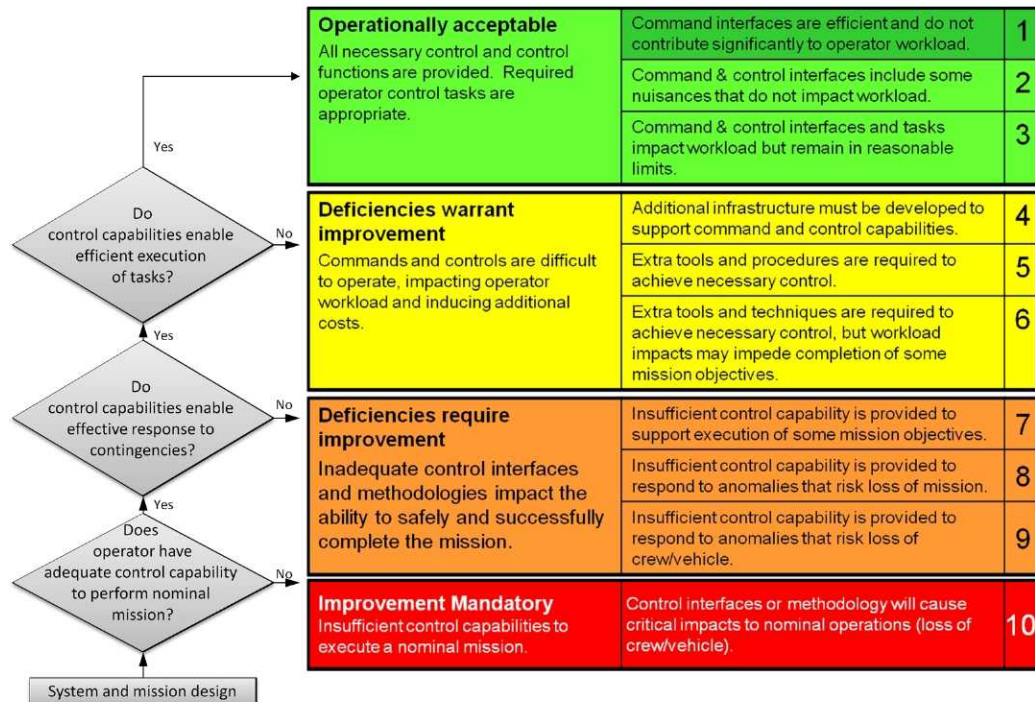


Figure 14. Detailed guidance for assessing control.

### **Acknowledgments**

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Cooper, G. E. and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," , *April 1969*.

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# **A Technique for the Assessment of Flight Operability Characteristics of Human Rated Spacecraft**

Alan Crocker

NASA Johnson Space Center



# Overview

- The Challenge – defining operability
- Role of Operability Assessment in a Spaceflight Program
- Spacecraft Flight Operability Assessment Scale Structure
- Initial Application & Lessons Learned

# What is “Flight Operability?”

(Exactly. That's the problem. There is not a formal definition.)

# We face challenges similar to those faced by test pilots and aircraft designers 40+ years ago.

- To improve aircraft designs, they needed a way to quantify the pilot's needs and criteria for aircraft handling qualities ("Stick and rudder" feel)
- George Cooper and Robert Harper – a test pilot and a test engineer - devised a scale to meet this need.
  - The scale evolved over a period of 12 years to become the modern version (1957-1969)
- Today, the Cooper-Harper Scale is the standard accepted means for specification of aircraft handling
  - Even Constellation has a Cooper-Harper rating requirement.



**The human spaceflight community needs a similar method to clearly characterize flight operability – and communicate operability issues - as we execute the design process.**



## Goal: Establish a framework for assessing operability concerns.

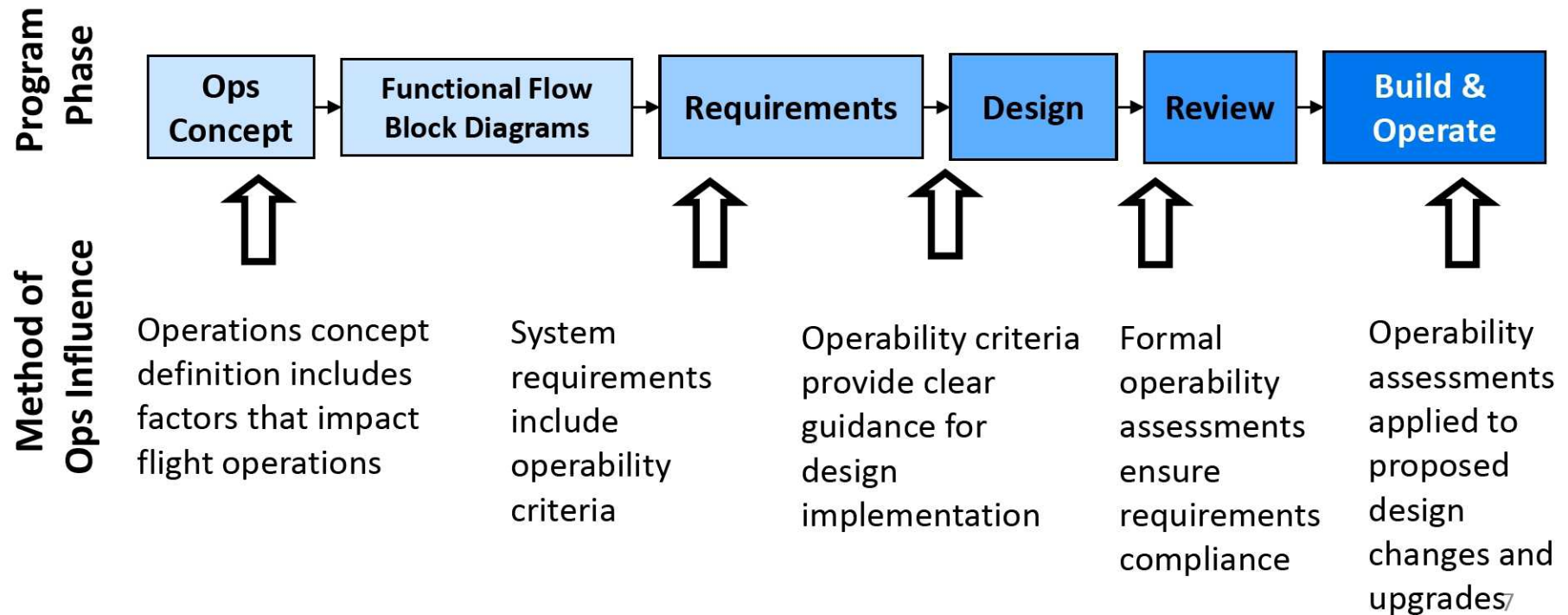
- Define general operational expectations and criteria.
  - Describe the key operations concerns.
  - Establish criteria for evaluation of those concerns.
  - Map evaluation results back to impacts on program.
- Incorporate this framework into program systems engineering process and schedules.
  - Use this framework throughout the design and review process to organize and justify our ops inputs.

# Operability assessment fit into a larger set of processes.

- Operability issues are linked to safety, reliability, performance, etc.
  - There are other tools available to assess these topics
- An operability assessment tool should not replace other assessment tools, but rather add to the toolset.

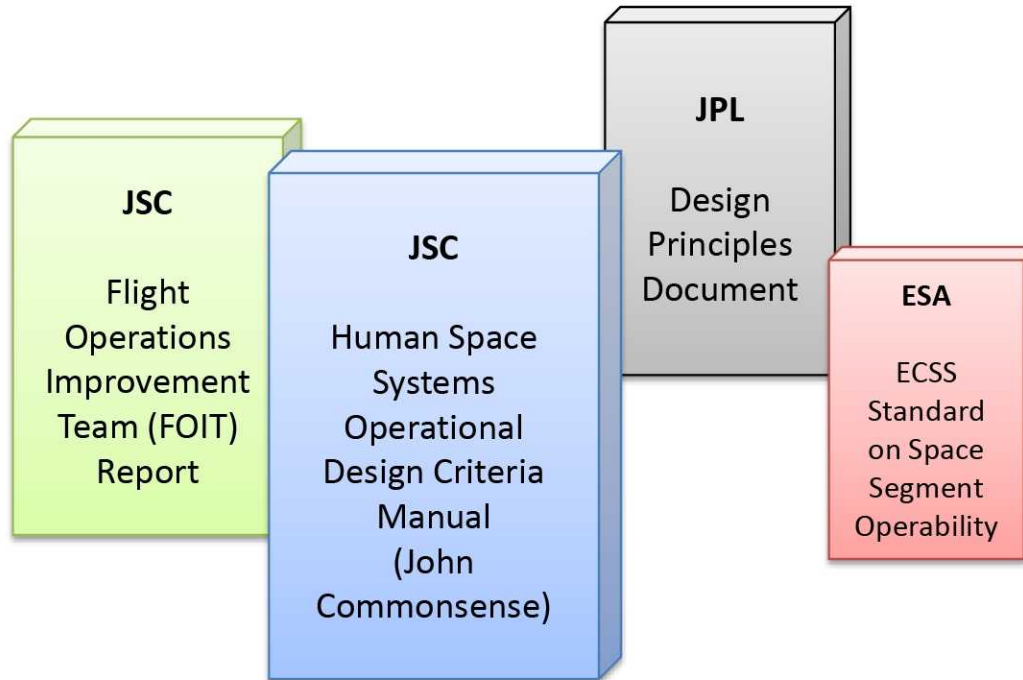


Formal definitions and criteria for operability can benefit the Program throughout its life cycle.





# There have been several attempts to define operability...

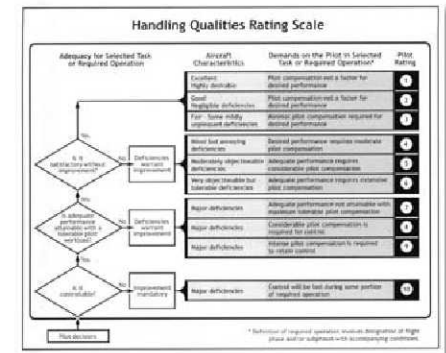


...but it remains difficult to establish formal requirements that completely reflect these needs.

# Why not use an existing scale like...

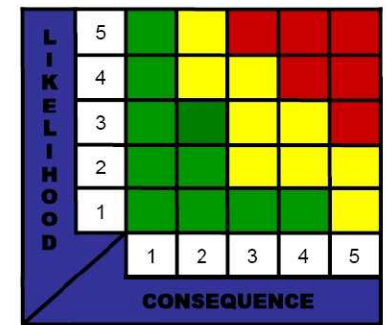
## ...Cooper Harper?

- Assessment requires availability of a simulator to perform evaluation.
- Only directly address the real-time aspect of mission operations (“Fly” vs. “Plan-Train-Fly”).



## ...or a risk matrix?

- Too generalized to completely reflect operability drivers.



But we can use ideas from both in building an operability scale.

# There are three key elements to this framework:

## Operability Factors

- Capture the general factors that drive ops complexity
- Include description of desired characteristics in each theme

## Criteria

- General questions that characterize operations impact
- Can be customized for each theme

## Grading scale

- Define the range of possible scores and their implications to ops and the program
- The resulting grades must have meaning for both the operations community and the program management community.

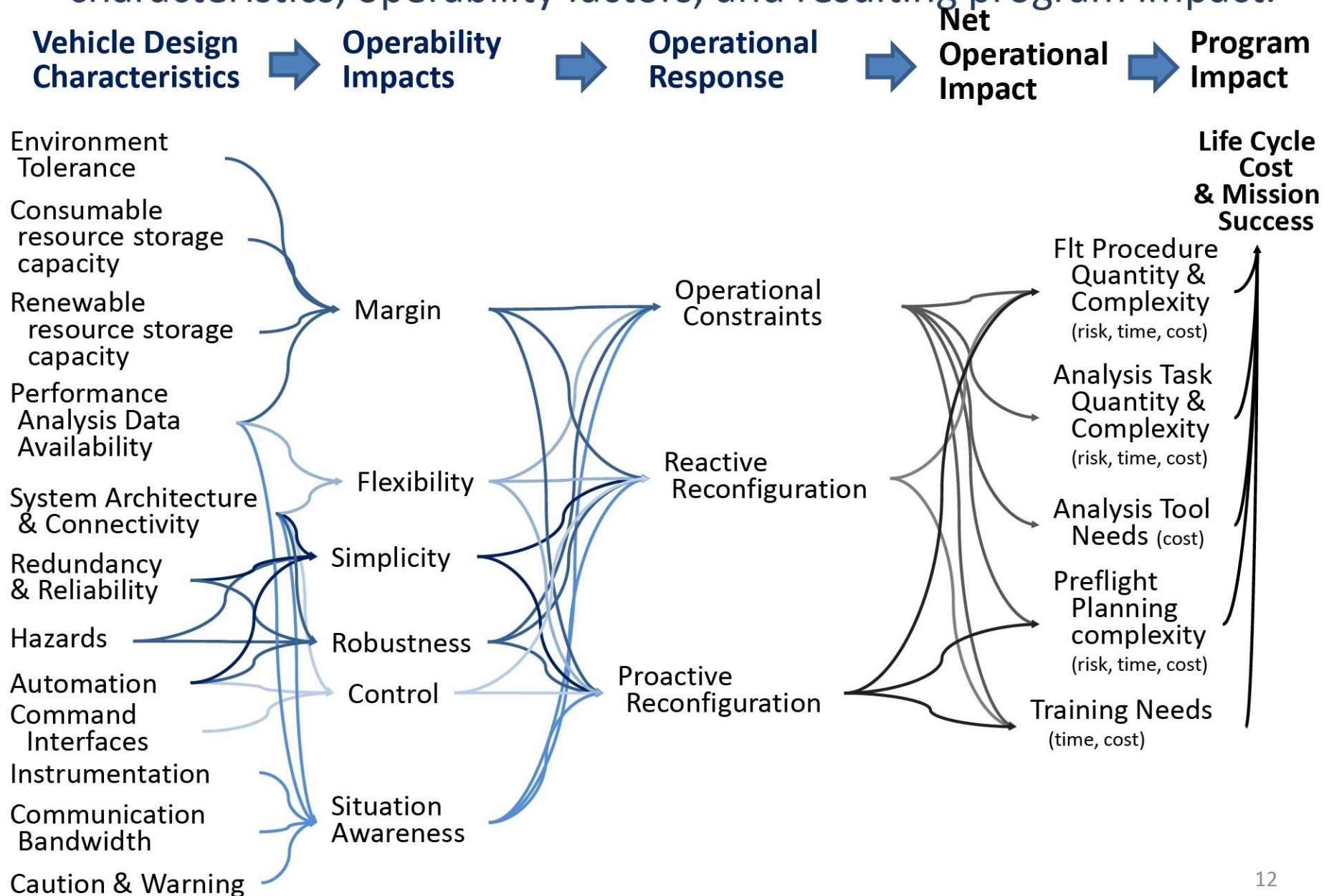
**These elements are applied to a system design for a specific design reference mission or task**



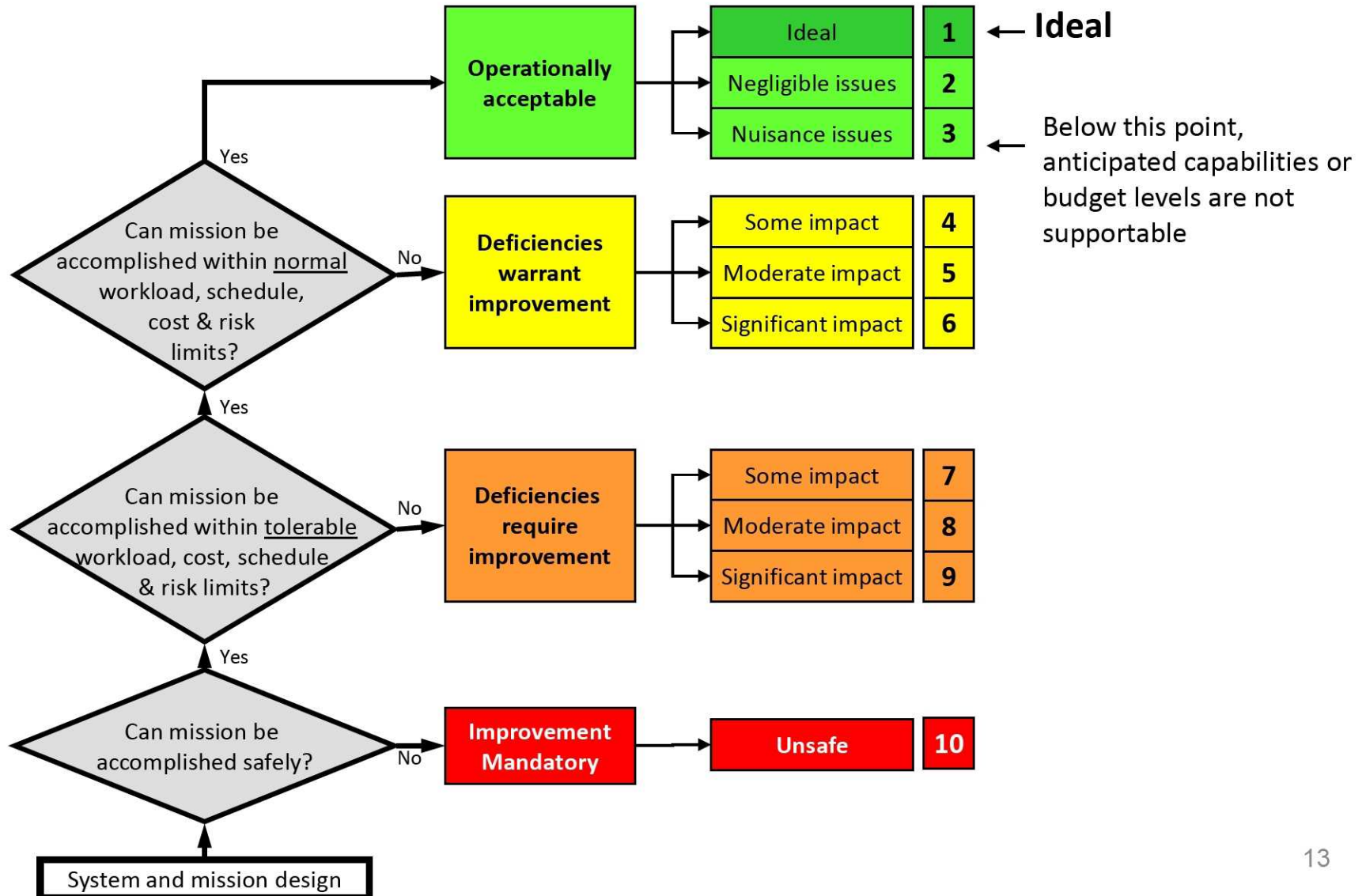
# Six operability factors capture the range of operational concerns.

- **Simplicity**
  - Commonality and consistency
  - Simple functions and interfaces
  - Simple tasks
- **Margin**
  - Performance margin
  - Resource margin
  - Environmental tolerance (temperature, radiation, etc.)
- **Flexibility**
  - Easy reconfiguration
  - Ability to make minor updates (limits, control gains, etc.)
  - Ability to upgrade through life cycle
- **Robustness**
  - Fail operational
  - Graceful degradation
  - Appropriate automation time-critical reconfiguration
- **Situational Awareness**
  - telemetry and caution & warning
  - Sensor locations and quantities
  - Simple indications for the operator
- **Controllability**
  - Command capabilities
  - Control of automated capabilities
  - Systems operate in a repeatable, predictable manner.

There are many complex relationships between design characteristics, operability factors, and resulting program impact.



# General criteria apply to all themes.





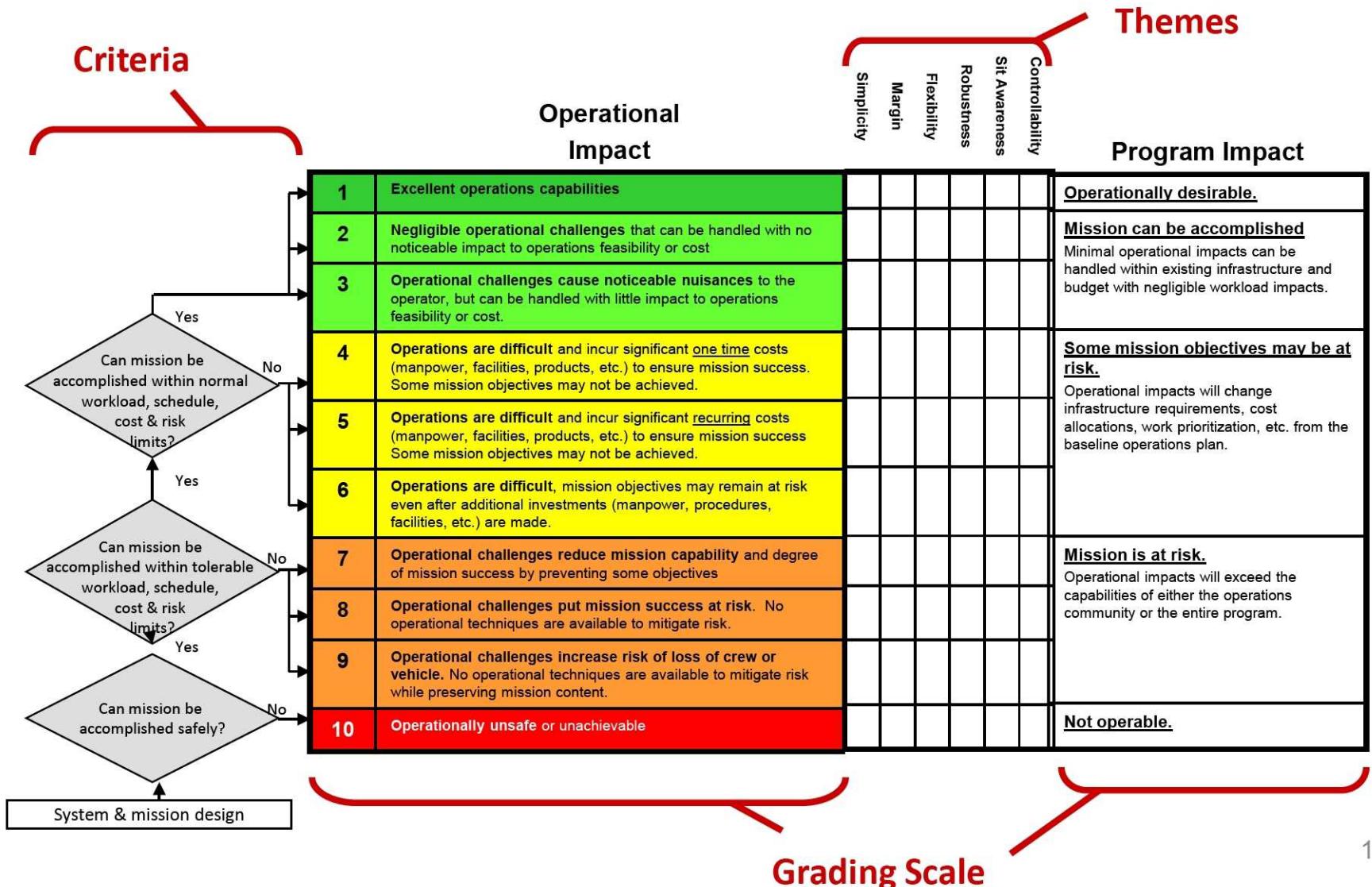
# The grading scale translates results into ops and program impacts.

## Operational Impact

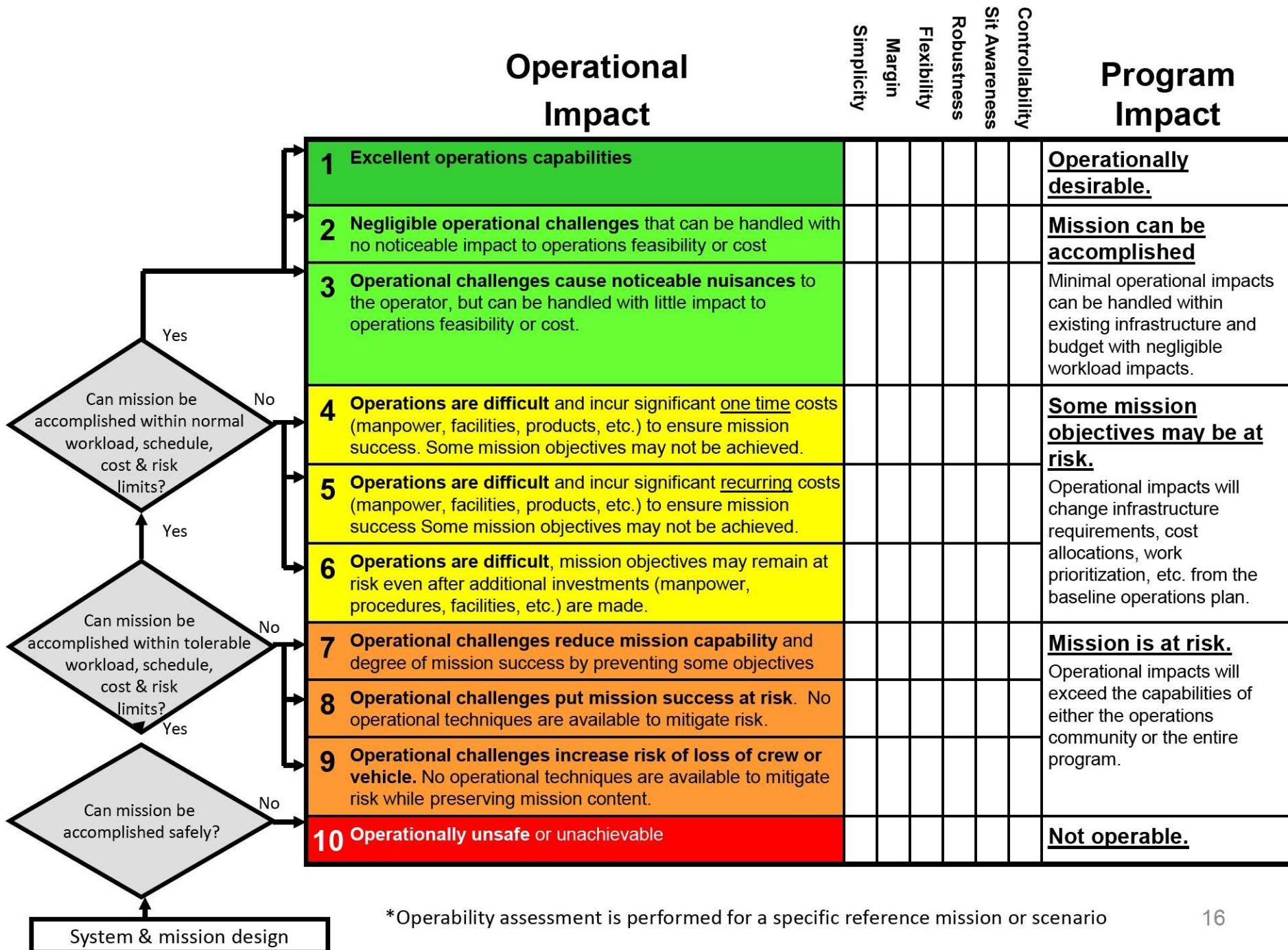
## Programmatic impact

<b>1</b>	<b>Excellent operations capabilities</b>	<u>Operationally desirable.</u>
<b>2</b>	<b>Negligible operational challenges</b> that can be handled with no noticeable impact to operations feasibility or cost	<u><b>Mission can be accomplished</b></u> Minimal operational impacts can be handled within existing infrastructure and budget with negligible workload impacts.
<b>3</b>	<b>Operational challenges cause noticeable nuisances</b> to the operator, but can be handled with little impact to operations feasibility or cost.	
<b>4</b>	<b>Operations are difficult and incur significant <u>one time</u> costs</b> (manpower, facilities, products, etc.) to ensure mission success. Some mission objectives may not be achieved.	
<b>5</b>	<b>Operations are difficult and incur significant <u>recurring</u> costs</b> (manpower, facilities, products, etc.) to ensure mission success. Some mission objectives may not be achieved.	<u><b>Some mission objectives may be at risk.</b></u> Operational impacts will change infrastructure requirements, cost allocations, work prioritization, etc. from the baseline operations plan.
<b>6</b>	<b>Operations are difficult, mission objectives may remain at risk</b> even after additional investments (manpower, procedures, facilities, etc.) are made.	
<b>7</b>	<b>Operational challenges reduce mission capability</b> and degree of mission success by preventing some objectives	
<b>8</b>	<b>Operational challenges put mission success at risk.</b> No operational techniques are available to mitigate risk.	<u><b>Mission is at risk.</b></u> Operational impacts will exceed the capabilities of either the operations community or the entire program.
<b>9</b>	<b>Operational challenges increase risk of loss of crew or vehicle.</b> No operational techniques are available to mitigate risk while preserving mission content.	
<b>10</b>	<b>Operationally unsafe or unachievable</b>	

# Themes, criteria and grading scale are integrated into an evaluation table.



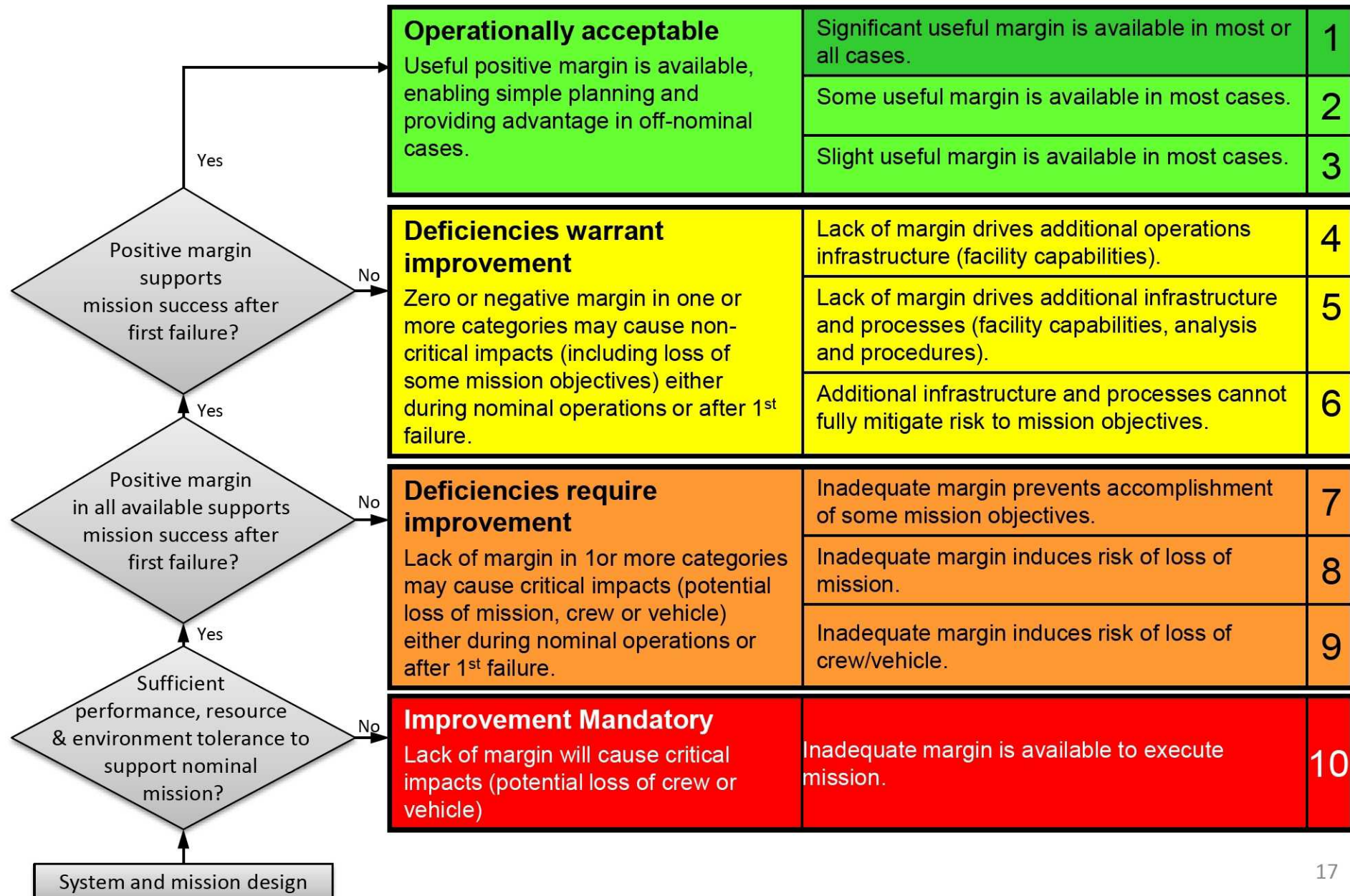






# For each operability theme, more detailed guidance is given

(Example – margin)



# Initial Application & Lessons Learned

Establishing a baseline for future assessments

- **Executed an initial operability assessment of Space Shuttle flight systems**
  - This was the first real exercise, using well understood design and a wealth of operational experience.
  - Provided guidance and criteria for assigning operability scores, but recognized that this first attempt would show variations from reviewer to reviewer
- **Goals**
  - Identify the major gaps in defined criteria
  - Explore possible interpretations of the criteria as written
  - Begin working towards a consistent approach for all technical disciplines.



## Scope of Space Shuttle Assessment

- Six major flight systems (with a total of 46 subsystems contained therein)
  - Communications
  - ECLSS
  - EPS
  - GNC
  - Mechanical
  - Propulsion
- Three major mission scenarios
  - Ascent
  - Orbit
  - Entry

High degree of similarity

# Initial Application

## Example – Evaluation of Shuttle Docking system for on-orbit operations

Operability Theme	Score	Description	Operational Impact	Program Impact
Simplicity	5	Multiple nominal and off nominal procedures as well as operational workarounds to disable and release dampers indicate inherent undesirable complexity in the system.	Complexity increases operator workload, requiring additional tools and techniques (procedures, constraints, etc.).	Some mission objectives may be at risk.
Margin	8	Little margin is available in the APDS hooks. Single hook out cases drive the need for significant system workarounds (PMA hooks, FR constraints etc). Single point jam on the ball screw mechanism could lead to loss of mission.	Inadequate margin induces risk of loss of mission.	Mission is at risk.
Flexibility	3	The semi-automatic docking sequence allows for much greater system flexibility but also poses issues with added training due to it's complexity.	Functions enabling flexibility induce additional operator workload within reasonable limits.	Mission can be accomplished.
Robustness	8	Capture latches require manual reconfiguring after the first failure to return to a nominal configuration. A single point jam on the ball screw mechanism can cause loss of mission.	Inability to recover sufficient functionality increases risk of loss of mission.	Mission is at risk.
Situation Awareness	3	In general, enough insight into the health and operation of the docking system is available to MCC. Some coordination with crew to attain crew only insight (A7 panel lights add to MCC workload.	Required effort to maintain Situational Awareness results in minor workload impacts.	Mission can be accomplished.
Control	3	Lack of ground control capability limits MCC ability to operate the docking system in off nominal situations.	Command & control interfaces and tasks impact workload but remain in reasonable limits.	Mission can be accomplished.



# Lessons Learned

- Defining flight operability is non-trivial. But Important.
- Development – and adoption – of a formal technique will take time.
- So far...
  - General acceptance of operability theme definitions in flight operations community
  - Evaluation process generates findings that can benefit future programs
  - Well received by program and development communities